TEST Engineering & Management

May – June 2020
ISSN: 0193-4120 Page No. 5433-5437

Prediction of the Mechanical Properties of Stainless Steel 304 Subjected to Fatigue Loading Using Artificial Neural Network

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Article Info
Volume 83
Page Number: 5433 - 5437
Publication Issue:
May - June 2020

Article History
Article Received: *19 November 2019*
Revised: *27 January 2020*
Accepted: *24 February 2020*
Publication: *17 May 2020*

Abstract

In this article, we use Artificial Neural Network (ANN) approach to develop a tool for prediction of the mechanical properties - elastic modulus and ultimate strength- of fatigued stainless steel 304 Specimens. The specimens have been subjected to fatigue loading starts from 10K cycles up to 80K cycles at different values of maximum stress (**σ** max). We noted that, at low magnitude of (**σ** max) as well as at the low cycling rate no substantial changes in elastic properties. When both number of cycles and (**σ** max) increase, reduction in elastic modulus and reduction in ultimate strength of the samples occurs due to formation of the microcracks. Such experiments are difficult to implement for different materials, different (**σ** max), and different number of cycles, so the aim of this paper is to build an ANN model to expect the mechanical properties with no need to implement the experiment. Very good agreement is achieved between the ANN model and the experimental data available.

Keywords: *Artificial neural network, elastic modulus, fatigue, stainless steel 304.*

I. INTRODUCTION

The paper aim is to predict the degradation in mechanical properties due to fatigue loading for structural elements by build artificial neural network (ANN) model based on experimental data. Experimental tests are done on commercial wide use stainless steel 304. This metal mainly used for many civil structure and different aerospace applications.

Most researchers are interested in evaluation of strength reduction of materials to avoid any sudden failure of structure during loading and running. The comprehensive study on this topic can be found in references [1]- [2].

From latest papers relevant to this study, we would mention [3] who studied the effect of fatigue strength and stresses on different elastic properties to come up with the non-linear relations. A study accomplished by [4] they were interested in evaluating the changes in the mechanical properties of stainless steel 316 subjected to cyclic loading with high number of cycles but limited strain, they concluded that in this range the yield strength increases while other properties remain almost constant. When cyclic loading applies on steel, at first stage strain hardening occurs and this leads to increase in the yield stress; this can be explained by generation of new cluster of dislocations. [4] –[5].

Standard error for prediction using neural networks has been studied by [6] who reveal that we can get low standard error using ANN prediction. Artificial neural network starts having many applications in mechanics of materials, I would mention some of these applications in [7] who predict the mechanical properties of hot rolled steel, the authors reveal that a single network with three outputs neurons are sufficient to address such problems. These results can utilize to develop a reference database for materials that can be used for different engineering applications; for instance, study the properties of industrial parts, enhancing rotating shafts, prediction the life of airplane engine blades …etc. for more Example of applications see [8] – [9].

Neural network algorithm acts as a ‘‘black box” system. It studies the relationship between input factors and the controlled variables by reviewing previously measured data, it operates similarly as a non-linear regression subroutine can do. [10].

As shown in literature, many researchers studied the

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relationship between fatigue strength and stresses, but I would say no study concentrate on the connection between artificial neural network and specifically stainless steel 304 materials to build a model to predict the mechanical properties for fatigued specimen in such non-linear cases and this give the novelty to this study.

In this work, Artificial Neural Network (ANN) has been successfully used to predict the mechanical properties of fatigued stainless steel specimens. ANN taught using the experimental data obtained for specimens subjected to fatigue stress for different number of cycles successfully used to predict the cyclic behavior and properties of steel. The results show a very good agreement between experimental and predicted values, it means that the ANN can be used with good confidence.

Artificial neuron consists of weight parameter, (w), bias, (b), and activation function named as, (y). Each neuron collects recorded data as: x1, x2, x3, denoting temperature, weight fraction, and strain rate (frequency). These input parameters are associated with a corresponding weight, w, which indicate strength of the connection between a given input and the respective output. Neural network consists of great numbers of interconnected processing blocks called "neurons" In our study, we use one hidden layer (processor) consists of a total number of 10 neurons. The basic features of artificial neuron are demonstrated in Fig. 1.
A bias, bi, can be defined as a sort of connection weight with a nonzero constant value extra to the summation of inputs and their corresponding weights. Mathematically, u, is given as

$$u_i = \sum_{j=1}^{3} w_{ij} x_j + b_i \quad (1)$$

Where, ui is transferred using an 'activation or transfer function", yi=f(ui), to yield an output. Then the errors in the output are introduced.

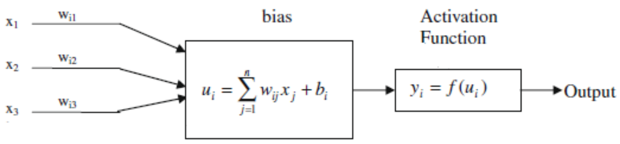

Fig. 1: Basic features of an artificial neuron

Back propagation algorithm is applied to adjust the weights, a slight change at a time, in a manner that decreases error. Training of the network is achieved by adjusting the weight level, w, and is processed through a several training sets like increasing number of neurons. In this study, the optimum architecture of the network was obtained by having one hidden layers and 10 neurons. The ANN model developed in this study is used to predict the elastic modulus and ultimate strength for stainless steel as affected by number of cycles, and ($\boldsymbol{\sigma}_{max}$).

II. Materials and Methodology

In my previous work [11]; Stainless steel 304 of thickness of 1.90 mm have been cut in standard specimen dimensions. The alloy composition stated by the manufacturer for the material is: C 0.08 max, Cr 18-20%, Fe 66.5-74%, Ni 8-10.5%, Mn 2% max, Si 1% max, P 0.045% max, S 0.03% max, Mechanical properties of this type of steel are, young's modulus 193 Gpa, Ultimate tensile strength 505 MPa, and yield strength is 215 Mpa.

Water jet cutting machine has been used with cooling hose to cut the specimens to ensure no changes in microstructure occurred during the cutting process and to keep the mechanical properties as stated. Geometry of the specimens was selected according to the ASTM 557M standard. MTS Landmark Hydraulic Fatigue machine was used to subject the specimen to cyclic loading rates starts from 140 MPa, 215 MPa, 237 MPa, 258 MPa and then 280 MPa. The number of cycles starts from 10K, 20K, 30K, 40K, and 50K cycles.

III. Results and Discussion

MINITAB software was used to study the effect of different parameters on examined parameters and to generate Pareto charts to reveal the interaction between inputs and their effect on output. Fig. 2 and Fig. 3 show the Elastic modulus and ultimate strength decrease rapidly with increase σ_{max}, while they decrease in less range with increase the number of cycles. It can be explained by nucleation of microcracks during low-cycle fatigue with σ_{max} higher than the material yield limit [12], [13]. To investigate the interrelation of the parameters on studied mechanical properties; Pareto charts have been established as shown in Fig. 4 and Fig. 5, it is clear that the σ_{max} has is responsible for the drop in ultimate strength from 600 MPa to 320 MPa and elastic modulus from 205 GPa to 130 GPa. ANN gives researchers a big picture on how much drop in elastic properties will occur if we keep increasing the fatigue stress σ_{max}. The interactions between these inputs almost do not affect the elastic modulus and ultimate strength according to Fig. 4 and Fig. 5. It means that a linear correlation between σ_{max} and the input parameters takes place.

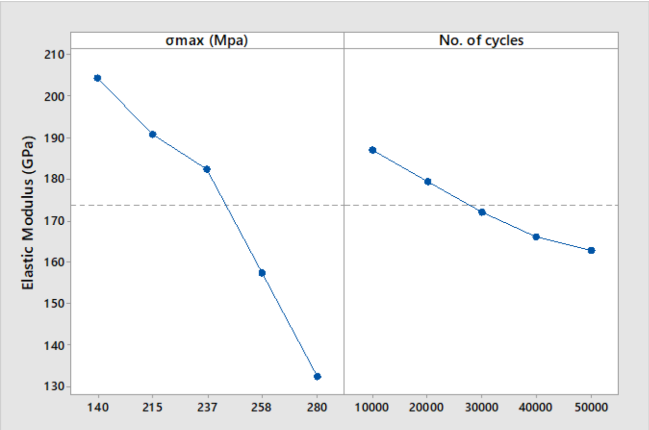

Fig. 2: Effect of loading rates and No. of cycles on the Elastic modulus.

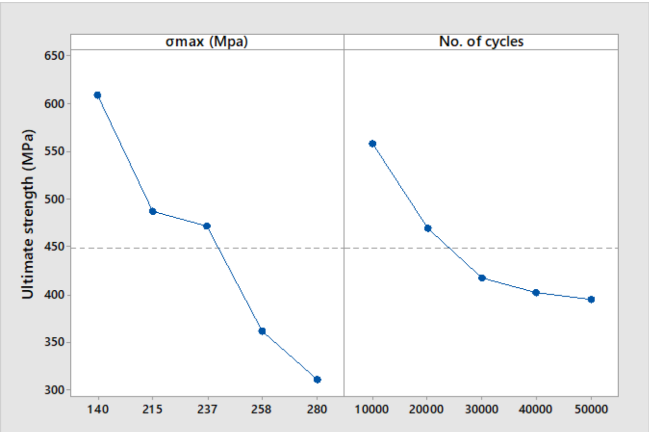

Fig. 3: Effect of loading rates and No. of cycles on the Ultimate Strength.

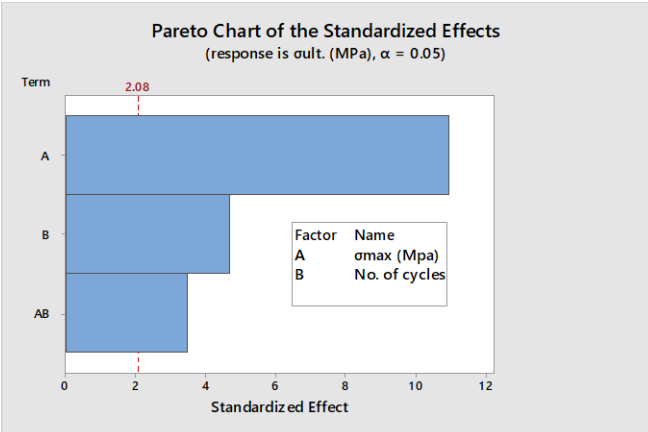

Fig. 4: The effects of correlations and interrelations of the inspected parameters on ultimate strength.

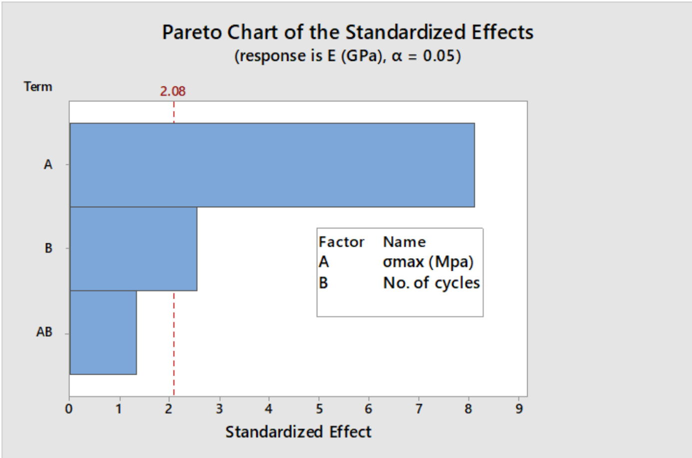

Fig. 5: The effects of correlations and interrelations of the inspected parameters on elastic modulus.

In such types of experiments, cost and time play a major role of limited the experimental work, the idea of this research is to predict the effect of input parameters (σ_{max} and number of cycles) on mechanical properties (elastic modulus and ultimate strength) using artificial neural network (ANN) without need to implement more experiments. For a given number of hidden neurons, the network is trained to calculate the optimum values of the weights and biases that minimize the error between the experimental data and ANN outputs [14]. The performance of the suggested ANN models for Elastic modulus and Ultimate strength are shown in Fig. 6 and Fig. 7, respectively. Fig. 8 and Fig. 9 show results of ANN testing; it is clear the excellent match between the real values and the ANN model with error less than 1.2% as shown in Fig. 10.

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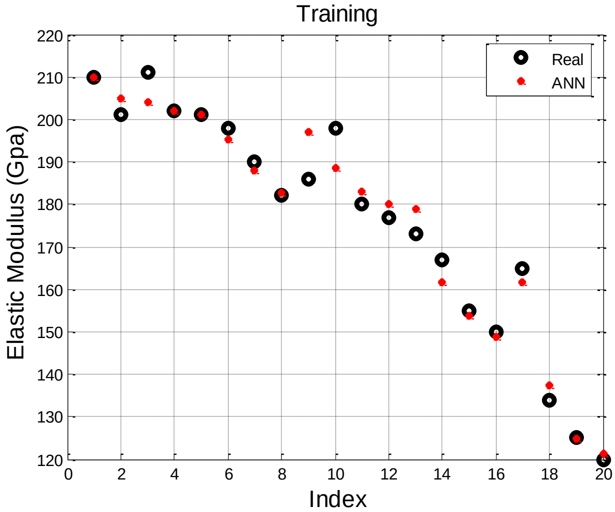

Fig. 6: Prediction of ANN and actual values for training sets for elastic modulus

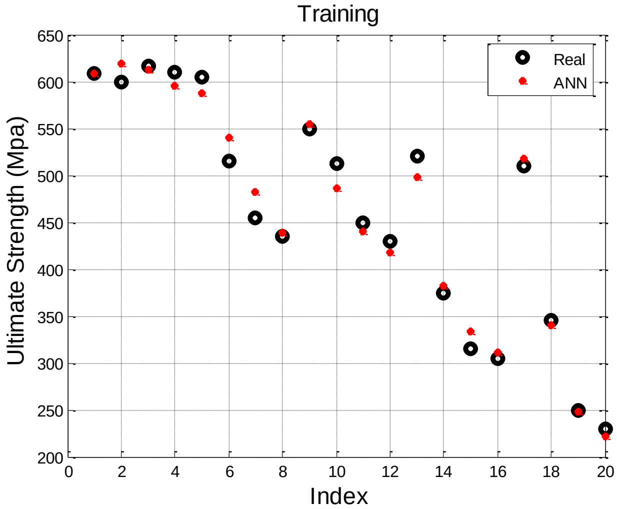

Fig. 7: Prediction of ANN and actual values for training sets for ultimate strength

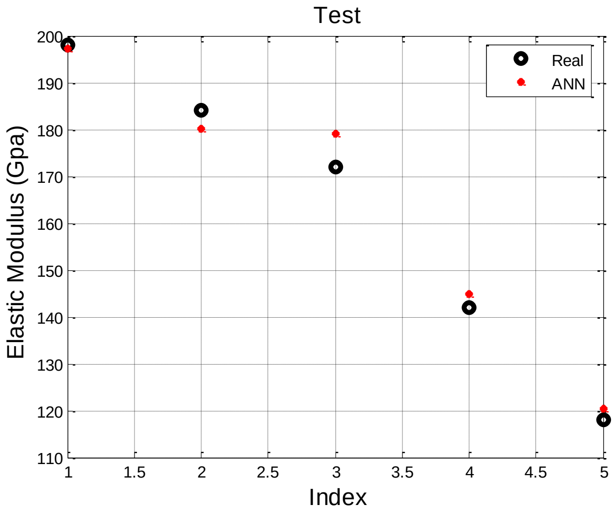

Fig. 8: Prediction of ANN and actual values for test sets for elastic modulus.

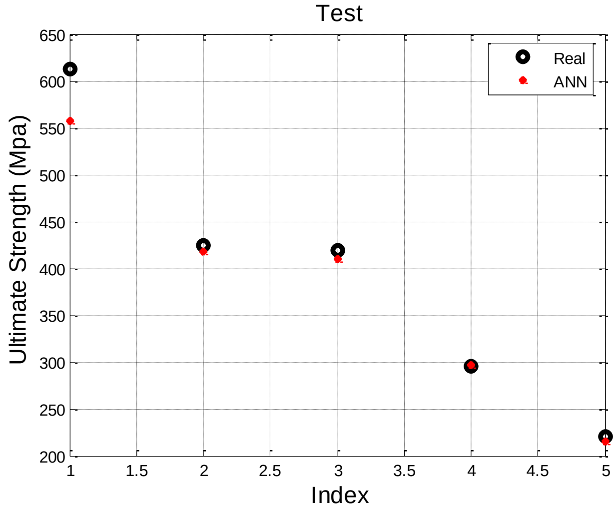

Fig. 9: Prediction of ANN and actual values for test sets for ultimate strength

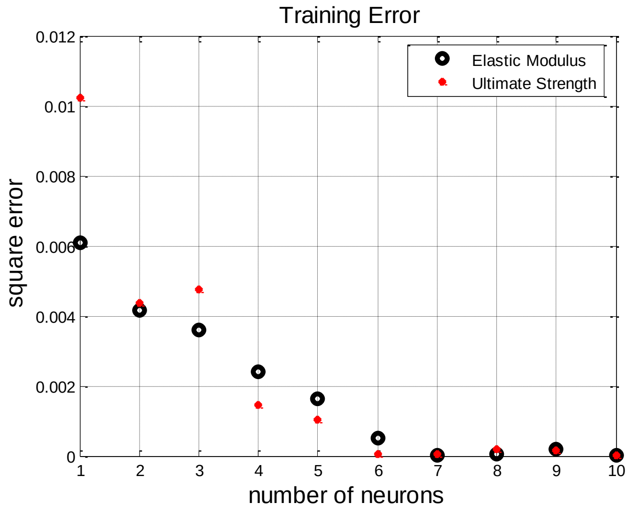

Fig. 10: Errors in both elastic modulus and ultimate strength

CONCLUSION

In this paper we focused on the effect of different factors; specifically, fatigue stress (σ_{max}) and number of cycles on ultimate strength and elastic modulus for stainless steel, the goal of this study is to build an Artificial Neural Network (ANN) approach to predict the behavior of material using ANN model. The big advantage of ANNs is the ability to model complex non-linear, multi-dimensional functional relationships without any prior assumptions about the nature of the relationships. As shown in results, The ANN model provides a great agreement between prediction and the experimental data.

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